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Safety Considerations for Laser Power on Metals in Contact with High Explosives-Experimental and Calculational Results

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SAFETY CONSIDERATIONS FOR LASER POWER ON METALS IN CONTACT WITH HIGH EXPLOSIVES- EXPERIMENTAL AND CALCULATIONAL RESULTS

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Measurements have been made to determine safe levels of laser exposure on common metals used in contact with high explosive (HE) samples. Laser light is often used on metals in contact with HE during alignment procedures and experimental data collection. The measurements look at temperature rise of the surface of the metal in contact with HE when laser energy is incident on the opposite side of the metal. The temperature rise was measured as a function of incident laser power, spot size, metal composition and metal thickness. Numerical simulations were also performed to solve the two-dimensional heat flow problem for the experimental geometry. In order to allow a single numerical simulation to represent a large number of physical cases, the equations used in the simulation were expressed in terms of dimensionless variables. The normalized numerical solutions can then be compared with the various experimental configurations used. Calculations and experiment agree well over the range measured.

INTRODUCTION

Lasers are commonly used in experiments involving high explosives (HE). During the setup phase of the experiments alignment lasers are often used to precisely locate optical measurements on the sample surface. The alignment laser sometimes consists of a high-power laser that will be used later in the experiment during detonation but is operated at a much-reduced power for alignment purposes. The most common modes of operation with these lasers are when the laser beam impinges upon an explosive encased in a metal and when the beam impinges directly upon the explosive's surface.

Most of the lasers operated in the alignment mode are of low enough power so as not to be of concern to experimenters during manned operation. Safety questions arise, however, when multiple-laser spots are focused onto the experiment simultaneously and when the laser spot size becomes very small, on the order of 100 μm or less. Additional concerns arise when a high-power laser is being used in an attenuated mode for alignment purposes. One must look at the maximum credible power that could reach the sample in a failure mode of the laser or the attenuation mechanism.

Calculations can be performed to estimate the maximum laser power that will cause a reaction and indeed, calculations should play a significant part in determining the safe level of operation. Calculations, however, should be verified by experiment before they are relied upon for safety purposes. Once a set of calculations have been experimentally verified then one might consider using such calculations to estimate power levels in new situations that have not been experimentally measured, but only if a strict set of calculational parameters are used pertaining to the new situation and the relationship of these parameters to safety considerations have been included in the previous experimental verification.

A methodology and philosophy of measurement need be established to make meaningful measurements to establish safety limits when working in manned operations where laser beams are impinging upon cased and bare explosives. One such method we have used at Lawrence Livermore National Laboratory (LLNL) is described in this paper. Numerical two-dimensional calculations performed at Kansas State University are our first attempt at finding the most simple approach to obtaining a good prediction capability.

EXPERIMENTAL

When the HE is encased in metal the only credible way for the CW alignment laser to create a problem is by heating the metal to a temperature that could cause a reaction to begin in the HE. The most thermally sensitive of the common explosives we use at LLNL, PETN, does not show significant exothermic reaction below a temperature of 150 C. By determining what laser and experimental parameters will produce temperatures of this order on the surface of the metal in contact with the HE we can establish a set of safe and practical guidelines.

To simplify the experiments one need not even use HE as long as a material that simulates its thermal conductivity is placed on the back surface of the metal under test. These experiments explore the temperature rise of the surface of a metal plate opposite the laser irradiation as a function of incident laser power, laser spot size, type of metal and the thickness of the metal.

The experimental arrangement is shown in figure 1. A 7.62 x 7.62 cm square of metal was clamped to an aluminum holder which served as a heat sink for the experiment. The distance from the irradiated spot to the holder was 3.5 cm. A 1.0 cm thick piece of Styrofoam was epoxied to the back of the metal to simulate the worst case thermal conductivity of typical explosives. A type K thermocouple junction was placed on the back surface of the metal, under the Styrofoam, directly behind the position of the irradiated spot which is on the opposite surface of the metal. A small dab of vacuum grease was placed on the thermocouple junction- metal interface to aid in the thermal contact. The junction itself was 1.0 mm in diameter.

The procedure used was to first use very low laser power to align the beam spot on the target metal. Next the sample holder was removed and a Coherent Beamcode analyzer was put in its place to measure the spot size. This step can be repeated for various sample

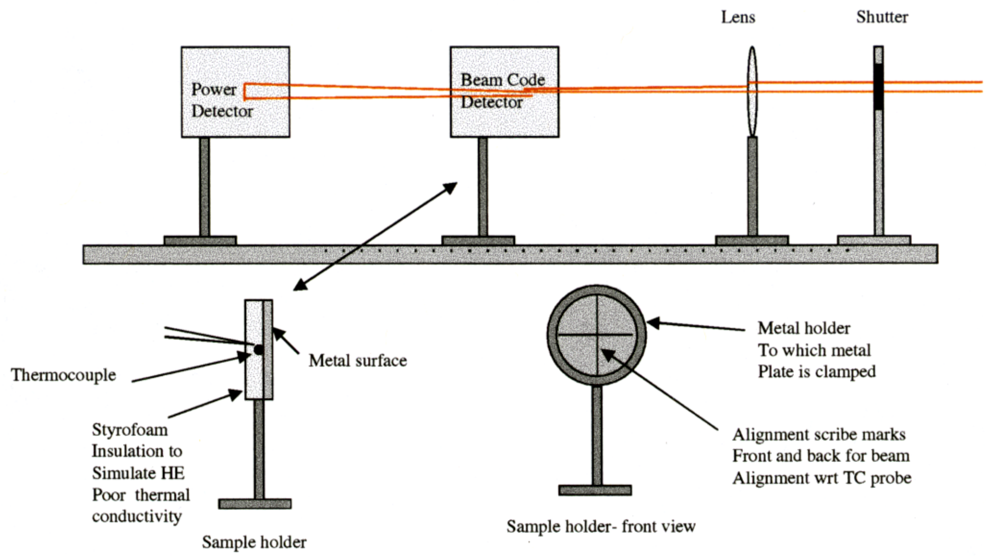

Figure 1. Experimental arrangement for measuring laser-induced temperature changes in metal plates.

positions along the railing and the railing position marked for various spot sizes. The beam diameters were measured at full width, 10% maximum. The Beamcode detector was then removed allowing the beam to be collected by a Coherent 210 power meter. The laser power was then adjusted to the desired level. The laser was shuttered and the sample holder put back into place. The shutter is then opened and temperature readings are taken for the prescribed amount of time.

The laser used in these experiments was a Spectra Physics Millenia X, 532 nm cw laser. The laser is capable of an output of 11 W which translates to about 8.6 W maximum on the samples due to loss in turning mirrors and lenses.

With so many variables to consider, the strategy was to map the parameter space in a way that could identify the important dependencies without measuring every combination possible.

CALCULATIONAL

The approach taken was to find the simplest simulation that would accurately match the experimental results. This requires a numerical solution to the two-dimensional heat-flow problem.

The assumptions used are that the metal is a thin plate of uniform thickness, clamped into a circular disk, and illuminated on one side, at the center, by a laser beam. For these calculations, it is assumed that there is no heat flow from the surface of the plate (except for the heat flow into the plate from the laser beam). The temperature is assumed to be fixed at the radius of the circular clamp.

The heat flow equation may be obtained from:

$$H = -k\nabla T \qquad (1)$$

where H is the heat flow, k is the thermal conductivity, and T is the temperature. The conservation of energy implies $\nabla \bullet H = -du/dt$

where u is the specific internal energy. Further, du/dt = CdT/dt where C is the specific heat of the material at temperature T. The result of these equations with eq.1 is

$$\nabla^2 T = (C/k)dT/dt \qquad (2)$$

When thermal equilibrium is reached, T obeys Laplace's equation: $\nabla^2 T = 0$.

In order to allow a single numerical simulation to represent a large number of physical cases, the equations to be simulated should be expressed in terms of dimensionless variables. We choose the thickness of the plate, taken to be w, as the unit of length. The normalized coordinate perpendicular to the flat surface of the plate will be z, which is actual length divided by w. The normalized radial coordinate is r, so that $0 \leq r \leq R/w$, where R is the radius at which the plate is clamped with the circular clamp. Then eq. 2 becomes

$$(1/r)\partial/\partial r(r\partial T/\partial r) + \partial^2 T/\partial z^2 = 0, \qquad (3)$$

where symmetry in the rotation about z and thermal equilibrium are assumed.

If the laser beam has a total power P and effective radius r_l, the power density in the beam is $P/\pi r_l^2$. At constant power density, eq. 1 shows the normal derivative (on the z=0 side of the disk with respect to the dimensionless coordinate z) at the place of laser incidence is

$$-\partial T/\partial z = (1 - \rho)Pw/(\pi r_l^2 k) \qquad (4)$$

where ρ is the reflection coefficient for the laser beam at the metal surface. To allow a simple value of one for the normal derivative boundary condition for numerical simulation we replace the actual temperature T by F' with

$$T = (1 - \rho)(Pw/(\pi r_l^2 k))F' \qquad (5)$$

Now the fully normalized equation is eq. 3 with T replaced by F' and with boundary conditions $\partial F'/\partial z = -1$ on $z = 0$, $0 \leq r \leq r_l/w$.

On numerical simulation it is observed that the radial flow of heat becomes uniform throughout the radial cross section of the metal disk before r = 10 for cases having $r_l/w < 8$. Thus it is sufficient, for disks having $R/w > 10$ to carry out numerical simulation only to r = 10 and use an analytic solution for r > 10. For r > 10 one has no variation in z so the problem becomes one-dimensional with analytic solution

$$F' = -K\ln(rw/R) + F0', \qquad (6)$$

where F0' is the normalized ambient temperature at the clamped radius R of the plate. This results in boundary condition for the simulation of $F' = -K\ln(10w/R) + F0'$ at r = 10.

Next, note that conservation of energy in the steady state heat flow requires that the total heat flux in equals total heat flux out. Thus since normalized heat flux density out can be expressed at r = 10 as $-\partial F'/\partial r = K/r = K/10$ and normalized heat flux density in has been taken as one, the requirement becomes $2\pi 10K/10 = \pi(r_l/w)^2$ or $K = (1/2)(r_l/w)^2$.

Finally, we replace F' by $F = F' - F'|_{r=10}$ so that the equation to be solved numerically and its boundary conditions are

$$\begin{aligned} &(1/r)\partial/\partial r(r\partial F/\partial r) + \partial^2 F/\partial z^2 = 0, \qquad (7)\\ &\partial F/\partial z = -1, \quad z=0, \quad 0 \leq r \leq r_l/w,\\ &F = 0 \quad 0 \leq z \leq 1, \quad r = 10, \text{ and}\\ &\partial F/\partial n = 0, \quad \text{all other surfaces} \end{aligned}$$

Thus the problem has been reduced to a two-dimensional, one parameter (r_l/w) study (as long as the parameter R/w is sufficiently large).

The relationship of normalized to unnormalized values is

$$T = (1 - \rho)(P\,w/(\pi r_l^2 k))\,\{F + (1/2)(r_l/w)^2 \ln(R/10w)\} + T_0 \qquad (8)$$

SIMULATION RESULTS AND COMPARISON WITH EXPERIMENT

Numerical simulations were run for r_l/w values 0.05, 0.1, 0.2, 1, 2, and 4. Calculations were carried out using "Student's QuickField[1]. Calculations for F vs. r for the values of r_l/w are shown in fig. 2 for temperatures on the face of the plate opposite the point of the incident laser beam (the side that would contact the HE).

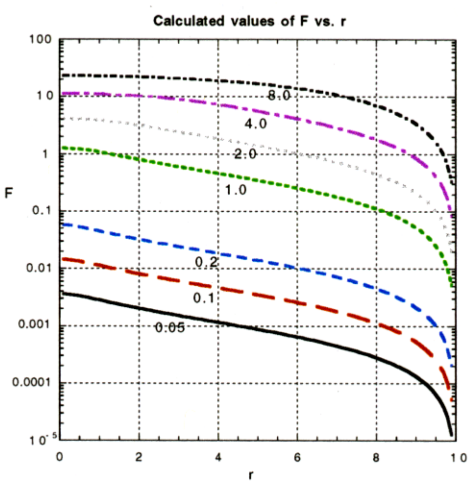

Fig. 2. Calculated values of F vs. r for various values of r_l/w.

To check how well these predictions agree with experiment we first take the case of 0.254 mm thick Cu and a laser beam radius of 0.25 mm with powers ranging form 1 to 8 W. We assume that the thermocouple probe measures the average temperature under the area of contact with the metal. From figure 3 we can get an average value of F to use in this calculation. Using this value of F and equation 8 with a value of .46 for the reflectivity of Cu, we get the results shown in fig. 4.

We note that there is reasonably good agreement but the data and experiment do differ by about 10%. In fact, a 10% change

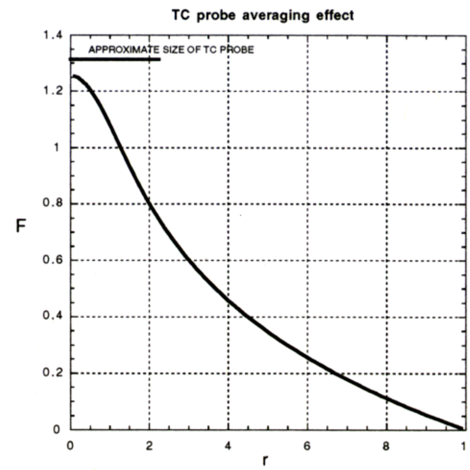

Figure 3. Relative size of the TC probe in relation to the temperature drop off for $r_l = 1$.

in the value of reflectivity we used, .51 instead of .46, would make the data agree very well. We suspect this is the explanation for the disagreement since the reflectivity of Cu changes very rapidly in this region of the spectrum.

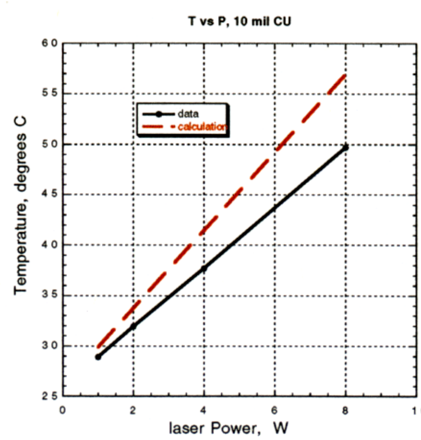

Figure 4. Calculated and experimental curves for the temperature of a .254 mm thick Cu sample irradiated with a .25 mm radius beam.

Likewise, when we plot the calculated values of temperature vs. power along with the data of stainless steel we get reasonable, but not exact agreement (fig. 5). Again an adjustment in the value of the reflectivity from .56 to .52 woud make the data and calculations agree.

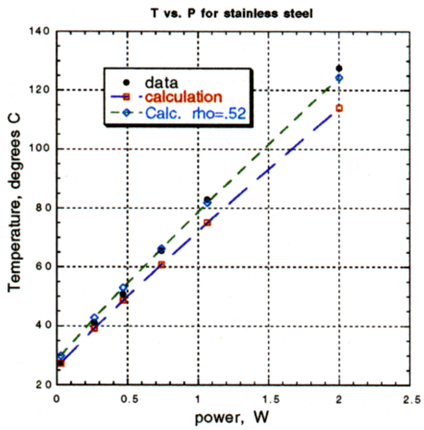

Figure 5. T vs. P for stainless steel compared with the calculated values using two different values of the reflectivity.

It should be noted that at higher power levels than 2 W with stainless steel that other mechanisms of heat removal start to become significant and the calculations are not valid. Radiation and convection both will play a part by cooling the front surface of the sample. Figure 6 shows a calculation of the front and back surfaces of a metal and one can see that the temperature on the front side is about a factor of 4 greater than the backside . This temperature difference does vary with spot size but for the cases we tested the variation was no greater than 4. Since radiation goes as σT^4 where σ is the Stefan-Boltzmann constant, the front side of the plate will radiate at a rate of approximately 256 times that of the back. This effect will lower the temperature measured on the backside with respect to the simulated value. For the purpose of this study, however, such high powers are only of academic interest since one would almost never expect to see CW alignment powers at this level.

The variation of the temperature on the backside of the metal with respect to the laser spot size is also of interest from the safety standpoint. To investigate this, stainless steel was once again used since the temperature rise is greatest, and thus easier to measure . Holding the power constant, the spot size was varied from .1 mm diameter to .822 mm diameter. This is a power density variation from 188 W/cm^2 to 12,700 W/cm^2

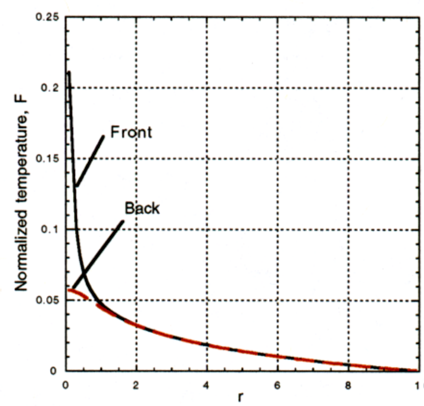

Figure 6. Calulation of the front side and backside temperature vs. r for $r_l/w = 0.\ 2$.

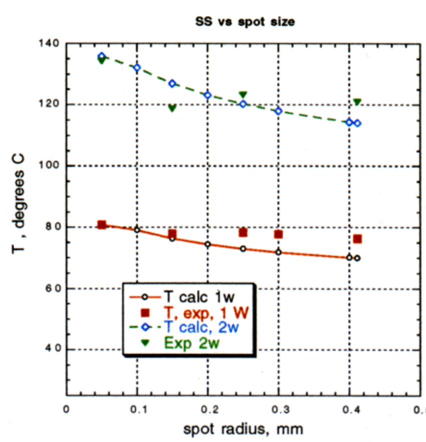

Figure 7. Temperature vs. spot diameter on the backside of a .254 mm thick stainless steel plate. Solid lines are the calculated values.

Figure 7 shows the experimental results compared with calculation.

The peak temperature on the back side of the plate opposite the point of incidence of the laser beam decreases as the beam radius increases while the total power in the beam remains constant. This dependence is somewhat weak and, for sufficiently small beam radii, the temperature levels off and does not increase further.

Another parameter of importance is the thickness of the metal. Experimentally we chose Al for this study because of the availability of thin, uniform samples of material. Figure 8 shows a plot of the temperature on the backside of the Al vs. the thickness of the Al for both experimental data and the numerical simulation.

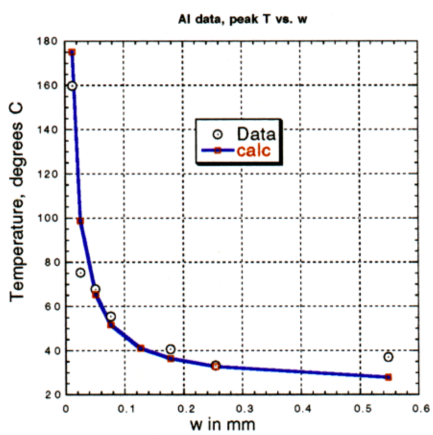

Figure 8. The temperature on the backside of Al as a function of the Al thickness.

The data were taken with a constant laser power of 4 W and a spot size of .1 mm diameter.

The agreement is rather good with the greatest departures occurring with the thin samples. The lower measured values of the two thinnest samples may arise because of the experimental arrangement.

In order to support such thin films of Al in the experimental configuration it was necessary to put a thin glass slide (.15mm thick) over the "laser entrance" side of the Al. Although the glass slide has a poor thermal conductivity compared to the Al, it is six to twelve times as thick and, therefore, can cause a non-trivial effect in the temperature measurement.

DISCUSSION

The numerical solution for temperature in a thin plate heated by a laser beam shows no surprises. The temperature rise on the side opposite the laser beam incidence only varies weakly with the size of the input laser beam. The dependence of the temperature on input laser power varies linearly and agrees well with the data. The temperature rise is fairly sensitive to values used for the reflectivity of the metal. Experiment and simulations also agree well for the temperature rise on the opposite side of the plate to laser incidence as a function of the metal thickness.

We have chosen a conservative approach for the amount of laser light allowed on explosive assemblies during manned operations. The data for encased explosives allow us to set some limits based upon safety margins deemed acceptable. For a 50 °C maximum temperature allowed for the explosive during laser irradiation (~30 °C above ambient), and for a .25 mm thick sample of the metals the following input laser power levels can be determined:

Cu	4.0 W
Al	5.0 W
Ta	0.7 W
SS	0.23 W

Note that these levels have an additional factor-of-two safety margin to account for the temperature distribution within the thermocouple junction area. The 50 °C limit is a factor of about 4 below the temperature at which PETN, the most thermally sensitive of the common explosives we used, shows some sign of reaction.

As a further safety margin, let's assume that we have a blackened area of the metal that will cause a total absorption of the laser energy. Using the values of the reflectivity in figure 9[2,3,4] we can adjust the safety margins downward for a totally absorbing material:

Cu	1.32 W
Al	0.35 W
Ta	0.34 W
SS	0.10 W

Most alignment intensities at LLNL are no more than 5 mW. There is occasion, however, when we desire to put multiple alignment beams on the explosive assembly. Assume we have 20 beams, each with a power of 5 mW, all concentrated onto a .2 mm diameter footprint. This worse case scenario then would have a total power of .1 W on the metal. This is the value for stainless steel that would cause a 50 °C temperature on the metal in the case of a totally absorbing area. Even though this scenario is unlikely we have determined that it has an unacceptable safety margin. If we limited the number of simultaneous beams to 5 this would buy us another factor of 4 in safety. Combined with the fact that or original temperature rise is a factor of 4 or more below the most thermally sensitive explosive we deal with, we now in reality have a factor of 16 safety margin for a worse case scenario.

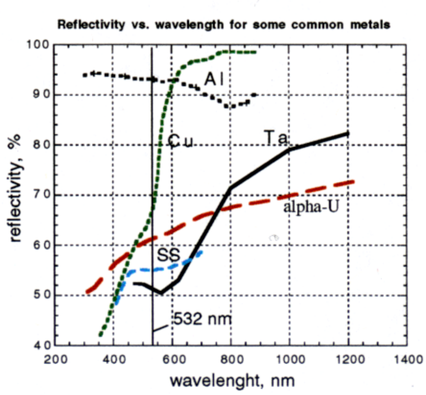

Figure 9. Reflectivity of some common metals[2,3,4].

Even though the majority of the data taken is at 532 nm, figure 9 shows that in the case of the four metals considered the curves are relatively flat or improve toward longer wavelengths in the range of 500 to 800 nm. This information, combined with the fact we have already taken a worse-case scenario where all of the laser energy is absorbed, there is no reason that any laser in this range could not safely be used under the above restrictions.

The simulations give good agreement and an understanding of what is going on, but should only be used as a rough guide in determining safety issues. One should not attempt to use these simulations outside of the limits of the assumption set forth in the definitions of the terms. If the simulations are to be used to predict a new materials behavior, the reflectivity and thermal conductivity of the material must be well known or the results can vary considerably. In the interest of safety, one can always assume the worst case where all of the laser light is absorbed and then use the calculations to get an upper limit.

Building upon this data base by adding new experimental results and verifying that the simulation code reasonably describes the results will expand our confidence in using the simulation to predict new materials and give us a larger base of experience from which to make safety decisions.

RECOMMENDATIONS

The following recommendations were incorporated into LLNL's safety procedures for manned operations involving laser power impinging upon high explosives:

- Alignment laser power shall be limited to ≤ 5 mW/spot when multiple-beam laser light is incident upon cased explosives.

• The spot size of the laser beam on the metal casing shall be limited to ≥ 0.2 mm.

• The thickness of the metal plate shall be ≥ 0.25 mm

• The number of spots allowed to be illuminated at one time shall be ≤ 20 for Al, Cu and Ta but shall be limited to 5 for SS. The only materials approved for use with the above limitations are: Cu, Al, Ta and stainless steel. All other metals shall be limited to one spot.

• The wavelength of the laser used be limited to the range from 500 nm to 800 nm.

• When a single laser beam is incident upon cased explosives the power level shall be limited to ≤ 25 mW with the spot size ≥ .2 mm and the metal thickness ≥ 0.25 mm for Al, Cu, Ta and SS. Temperature rise measurements must be made for all other metals and a peer review take place for power levels > 5 mW and ≤ 25 mW.

• The power shall be limited to ≤ 7 mW for a laser beam of 532 nm on the bare explosives listed in table 1. All other explosives must be measured at the laser wavelength to be used and a peer review take place before manned operations are allowed.

We believe these recommendations are safe and yet allow most alignment operations to take place without undue limitations. The recommendations are conservative but practical. Safety must always be the first concern when dealing with high explosives.

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